FIELD AND LABORATORY STUDIES TO ASSESS THE STATE OF HEALTH OF VALVE-REGULATED LEAD ACID BATTERIES: PART I CONDUCTANCE / CAPACITY CORRELATION STUDIES

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ABSTRACT

In the initial phase of this ongoing program, approximately 500 Valve-Regulated Lead Acid (VRLA) cells (both individual and 6 volt monoblocs) have been capacity tested and measurements made of conductance as well as conventional diagnostic parameters such as float voltage and specific gravity. Cells studied ranged from four to six years' service, from 200 to 1000 ampere-hour in size and included a group of 6 volt 200 ampere-hour monoblocs. Physical arrangements included 18 parallel strings of 48 volt 1000 ampere-hour cells, in a typical telephone transmission office; two and three parallel string configurations of 48 volt 200 ampere-hour cells in cellular telephone sites, as well as three parallel strings of 60 - 6 volt monoblocs in a UPS site. Although individual cell capacities ranged from 0% to 100%, within most of the strings evaluated, there was essentially no correlation of capacity with the conventional diagnostic parameters of float voltage or specific gravity. By contrast, correlation of conductance with capacity was universally high, and sufficiently good to allow statistical prediction of capacity to be made from individual cell conductance values. While additional capacity / conductance evaluations are still needed for other VRLA cells designs (especially Gel), other applications and other plant configurations, it can be stated that at this time, the use of conductance testing as a substitute for capacity testing of VRLA cells looks extremely promising, and has many advantages when compared to traditional diagnostic methods.

Additional data document the variety of discharge curve shapes shown by good, fair and poorly performing cells, and invite speculation as to their cause(s). Post mortem diagnostics are scheduled, and will be reported at a later date.

Finally, limited temperature test data, measured during discharge, show a significantly greater increase than would be expected in a vented (flooded) cell, of similar size and at similar rates. Additional data are needed to quantify this effect and determine necessary temperature correction factors for capacity discharge tests of VRLA cells.

BACKGROUND

Over the course of the last ten years, Valve-R gulat d L ad Acid (VRLA) batteries have demonstrated an extremely rapid introduction, eager user acceptance, and widespread application in many areas of battery usage. In telecommunications, th y have been increasingly applied as reserve batteries in both controlled central office switching and transmission environm nts, as w ll as in the more extreme environments of fiber optic vault and remote, exposed, subscriber loop cabinets. In addition, VRLA batteries have become a major factor in the application of cabinet-type high voltage (120 to 380 volts) UPS systems, designed to protect computer systems during loss of commercial A.C. power.

Unlike the more conventional flooded or vented lead acid batteries, measurement of cell specific gravity is not possible, while measurement of individual cell float voltages has not been shown to be indicative of the "state of health" of the cell, as measured by a capacity test. As a result, users have been forced to rely on actual cell or battery performance under load. This is expensive, cumbersome, requires special equipment, trained personnel, and most importantly, generally requires the battery string to be taken off line for an extended period of time, while the test is being performed, reducing the available battery reserve.

Since the expected failure modes of VRLA cells: dry-out; grid corrosion and loss of contact to the active material; jar bulging with subsequent loss of plate / separator / electrolyte contact; internal corrosion and loss of contact between post / strap / plate lugs; all result in an increase in cell impedance. or a loss of cell conductance, these techniques have been actively pursued as substitutes for capacity testing [1, 2, 3].

The possibility of developing an alternative to timed-discharge testing of standby cells and batteries was suggested by the work of DeBardelaben[1]. Using laboratory test equipment, DeBardelaben measured the complex impedance of lead-antimony telephone cells rated at 7,000 ampere-hours. His analysis disclosed a strong inverse correlation between cell capacity and either the magnitude of cell impedance or its resistive real part. Further laboratory studies by Vaccaro and Casson[2] showed that increased impedance and resistance were also good indicators of "dryout" of VRLA stationary batteries. However their studies showed a high degree of correlation between impedance and capacity, but only at very high (5-10 minute) discharge rates. A survey, by one of the authors[3], in the spring of 1991, showed only a very limited data base for correlation, with some data presented which showed no apparent correlation . Nevertheless, for the user, the need is real and urgent, to have available a technique other than capacity testing, for field testing and evaluation of VRLA cells.

This paper presents data obtained in an ongoing study, of the relationship between cell *conductance* and reserve capacity and does not include any measurement of cell *impedence*. Field tests have been performed on several hundred VRLA cells, in working telephone transmission and cellular offices and in UPS and other applications, measuring conductance, ampere-hour capacity, cell float voltages and other parameters which might be indicative of performance under load.

CONDUCTANCE TECHNOLOGY

Conductance is defined as the real part of the complex admittance. The authors have determined by empirical data and computer modeling that low frequency conductance, measured in the international unit: Siemens (or the American unit: Mhos), provides useful information about battery condition since it reflects the changing characteristics of a battery as it displays defects or shows signs of w ar.

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The electronic battery conductance testers used in the tests, were developed by Midtronics, Inc. for the purpose of instantaneously assessing the state of health and the stored energy capacity of 6 and 12 Volt monobloc batteries and individual 2-volt cells. Their operation is based upon an adaptation of the conductance testing technology first reported in a paper by one of the authors[4] and which has been successfully applied for over ten years, and widely accepted by major automotive manufacturers for testing the available cranking power of automotive engine-starting batteries.

The original problem of testing automotive batteries for use in engine starting applications had presented an entirely different problem. Unlike the reserve battery's mission of supplying energy over an extended period, the primary mission of a starting battery is to supply a large burst of power for a short duration of time. Accordingly, automotive batteries are conventionally tested by means of a short-duration (e.g. 15 second) load test. However, the load test, like the timed-discharge test, also requires heavy, cumbersome, equipment and suffers from other serious disadvantages.

In response to these problems, Midtronics first developed conductance test equipment to provide a practical alternative to the common load test. Measurements of conductance have been found to correlate strongly with a battery's power rating expressed in Cold Cranking Amperes and provide a direct measure of the battery's high-current cranking capability.

Because of variations in battery designs, manufacturing processes, extended discharge times, a variety of usages and differing failure modes, the conductance method developed for assessing cranking power could not be directly applied to the assessment of available ampere-hour capacity, as would be desired for batteries in reserve applications. Because of the time required and the complications associated with timed-discharge testing however, it would be obviously desirable to provide a simple, instantaneous, test - such as a conductance test - that could be used to assess stored energy capacity without requiring that the battery be discharged in the process.

Proprietary testing by one of the authors, measuring conductance at various frequencies as well as computer modeling, have shown that very low frequencies are most effective in distinguishing good batteries from worn or defective batteries based on conductance testing. Our research has indicated that while testing of cranking batteries is most effectively performed with a time-varying signal of approximately 100 Hz, that best results are obtained on standby batteries at even lower frequencies. Tests of batteries documented in this paper were taken at a frequency below 25 Hz for monoblocs, and near 10 Hz for individual cells. The appropriateness of these frequencies has been shown in the original work of Yahchouchi[5] reported by M. Alzieu[6] of Electricite de France.

Two types of conductance testers were used in these tests. The first type of tester, ("Celltron") is a fully-digital, self-contained, electronic device designed to measure voltage and conductance of single, two-volt, lead-acid cells; or of three-cell (6-volt) batteri s. The cell/battery undergoing test provides the very small (approximately 1.5 amp) current for measurement. In addition, the unit utilizes a seperate, 15 volt, nickel cadmium battery pack. The "Celltron" is electrically connected to the terminals of a cell/battery and measures its conductance with a small, time-varying signal of approximately 10 Hz. An internal conductance standard permits calibration checking by the user, to assure accuracy of the cell/battery measurements.

The second type of tester ("Midtron") is a self-contained, electronic device designed to measure battery voltage and conductance of either three-cell (6 volt) or six-cell (12 volt) lead-acid batteries. The Midtron is totally powered by the battery undergoing test and require no additional batteries or connections to external power. This tester is electrically connected to the terminals of the battery undergoing test and senses its conductance with a small, time-varying signal at frequency of approximately 25 Hz.

The majority of the individual cell tests performed and reported on were taken with the Midtronics Celltron conductance tester. Those tests made on multiple cell monoblocs were taken with Midtronics Midtron conductance testers.

EXPERIMENTAL

Telecommunication Transmission Office Correlation Study Strings 2 through 8.

In January of 1992, the first series of correlation tests was performed in a telephone transmission office. The plant containing the valve regulated cells consisted of chargers, batteries and distribution equipment. The charge portion of the plant consists of fourteen 400 amp ferro-resonant chargers with 480 volt 3 phase input power. The charging bus connects to the battery bus near the discharge end. There is a 10,000 amp charge shunt in the positive conductor of the bus between the last charger and the first battery.

The cells were arranged in strings of 24 cells to form batteries. There were 18 strings in the plant though only 15 strings were tested. The plant was designed to float the batteries at 54.0 volts.

The first group of tests was performed on eight banks of 24 c ll 1000 Ah (@ 8 hour rate) VRLA batteries. The approximate age of the battery was five to six years. The ambient temperature during the testing was approximately 60°F (15.5°C).

All eight parallel batteries (strings 1 through 8) were taken off line and left open circuit for approximately 72 hours prior to performing both the conductance and discharge testing.

The first part of the test included individual cell conductance measurements that were made utilizing the Midtronics Celltron cell conductance tester. Conductance data were obtained for 24 cells of each string prior to instrumentation for discharge testing. Each conductance and open circuit voltage measurement was made by simultaneously placing the Celltron probes onto both the positive and negative cell posts. Next, intercell connection conductance measurements were obtained for each connection. This was accomplished by leaving one of the probe connections on the positive post, and placing the other probe connection onto the adjoining cell post.

An Alber battery test system was used to perform discharge testing. The Alber system provided controlled load current, single cell monitoring and data storage. Data acquisition for each 24 cell string included: individual cell voltages, total string voltage, load current and elapsed time. A 263 amp constant load current to an

end voltage of 1.80 volts per cell was utilized for testing of strings 1 through 8. Individual cell discharge voltage data was acquired at five minute intervals and stored via hard disk. Due to the method used for instrumenting each cell for data acquisition, voltage drops from the intercell connections were included in the individual cell data and suitable corrections were made in processing the final data.

String 1 Conductance vs. Time during Discharge.
The same testing technique performed on strings 2 through 8 was utilized on string 1; however this discharge test was interrupted at 15 minute intervals, conductance measurements were made, and the discharge test was continued. The mean time for conductance measurements made on the 24 cells of string 1 was 0.25 minutes per cell or six minutes total.

Correlation Study Strings 9 through 15.
In April of 1992 a second set of correlation tests were performed in the telephone transmission office on seven additional 24 cell battery strings. The same cell type was studied (VRLA 1000 ampere-hour@ 8 hour rate). Float voltages were measured prior to taking the batteries off line. These batteries were left open circuit for approximately 36 hours prior to testing, and open circuit voltages measured. The ambient temperature was at 70°F (21°C). Both conductance and discharge tests were performed as described in the correlation study of strings 2 through 8. However the cells in strings 9 through 15 were all discharged to 1.75 volts per cell.

Individual voltage connections were used for the second set of tests that were performed on strings 9 through 15, and therefore voltage drop corrections for intercell connections were not necessary for processing the final data.

Temperature Measurements.
Temperature measurements were obtained for two discharge tests. Six cells of different conductances were monitored. A Fluke (Model 77) meter with a Fluke (80T-150U) thermocouple interface module were used for this test. Data were obtained by measuring both the top of the negative post and on the jar wall between adjacent cells. Temperature measurements were made at 30 minute intervals.

Cellular Telephone Sites.
Typical battery configurations located in the cellular telephone sites consisted of two and three parallel branches of 24 cell 48 volt batteries. The batteries were located in a controlled environment with both heating and cooling capabilities and typical temperatures of 70°F (21°C). Field testing performed at cellular telephone sites consisted of conductance testing in conjunction with timed discharge tests. A Fluke 87 multimeter was utilized for measurements of float voltage, Midtronics Celltron cell conductance testers were utilized for all conductance measurements and Alber discharge test equipment was utilized for all discharge tests performed at a particular site. The testing sequence performed on the cells at the cellular site consisted of: float voltage measurements, disconnecting one of the parallel branches and performing conductance measurements, cleaning and retorquing of intercell connections, instrumentation of discharge equipment and individual cell voltage monitoring. Both two hour and three hour discharge rates were typically utiliz d with nd of discharge voltages of 1.80 and 1.75 volts per cell.

UPS Application.
Field testing was performed in a UPS application containing 180 6 volt VRLA 200 ampere-hour monobloc batteries. The batteri s were configured in three parallel 60 - 6 volt monobloc battery strings that had been in service for approximately six years. Initial float voltage data were obtained with a Fluke 87 multimeter. One of the parallel branches was taken off-line and a sample of 20 batteries was tested to characterize the battery system. Th discharge test was performed due to the poor physical condition of the battery, based on a detailed visual inspection. Conductance measurements utilizing the Midtronics Celltron conductance tester were made immediately preceding the discharge test. An Alber load bank, controller and battery voltage monitoring system were utilized for discharge control, and data acquisition throughout the entire discharge test.

Railroad Signal Cell Testing
Conductance tests using the Midtronics Celltron cell conductance tester were performed on several VRLA 225 ampere-hour cells located in railroad signal sites. Typical ages for these cells were three to four years. Cells that were identified as having high and low conductance values were tagged and sent to Midtronics for discharge testing. Also two new cells of similar construction were also supplied to Midtronics for establishment of a baseline conductance value. Upon receipt, the cells were charged using a Firing Circuits (Digitron) programmable charge/discharge circuit, with individual cell voltage monitoring performed with Fluke Hydra 20 channel data logger. The cells were boosted according to the manufacturer's recommended constant voltage practice, rested for 24 hours, conductance measurements taken, and discharged at a constant current of 42 amps to 1.75 volts per cell. Two charge/discharge cycles have been performed to date.

RESULTS AND DISCUSSION

Conventional Parameters as Capacity Indicators
Figures 1, 2 and 3 show the distribution of float voltages for three representative 24 cell strings in the telephone transmission plant.

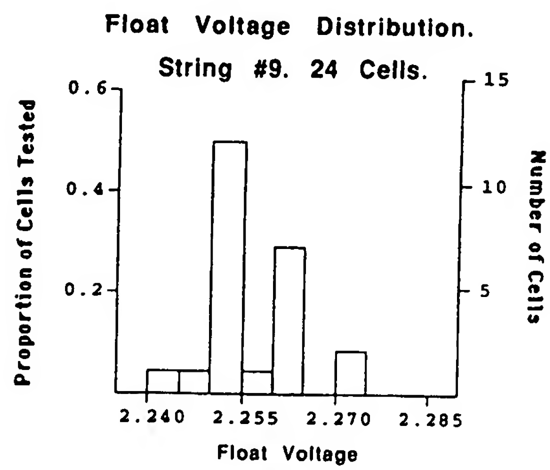


Figure 1

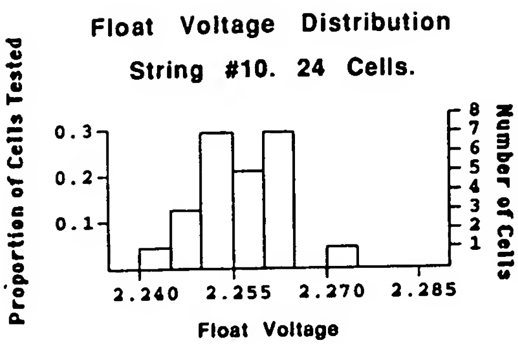


Figure 2

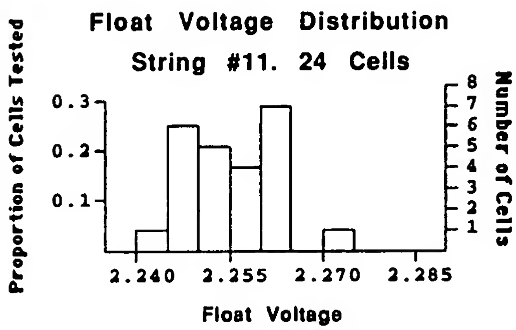


Figure 3

Figure 4 shows the same parameters for the 168 cells of strings 9 through 15 considered as a group. While they may not be "ideal" normal distributions, they clearly show that float voltages are all within nominal specification values recommended by the manufacturer.

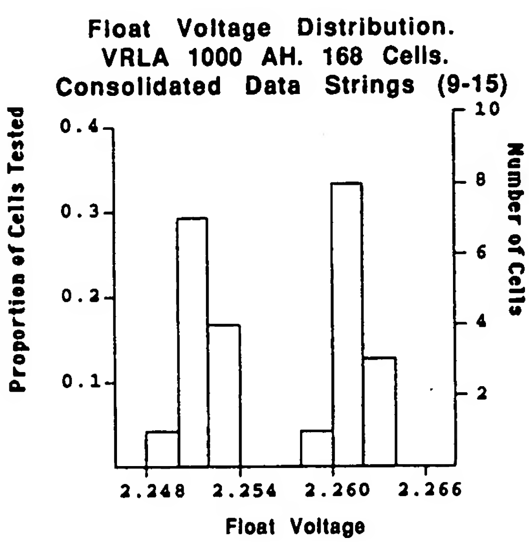


Figure 4

Figures 5, 6 and 7 show the distribution of capacities to 1.75 volts per cell in the same three representative strings from the 9 through 15 group.

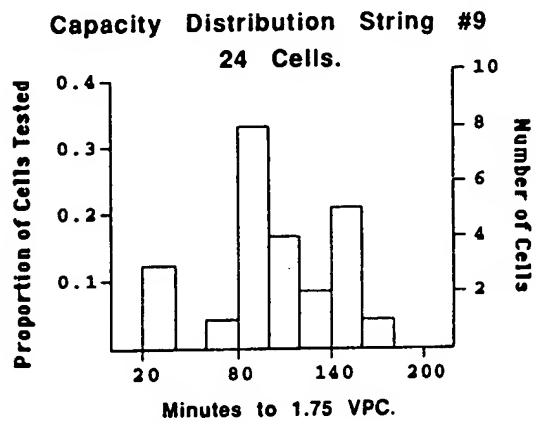


Figure 5

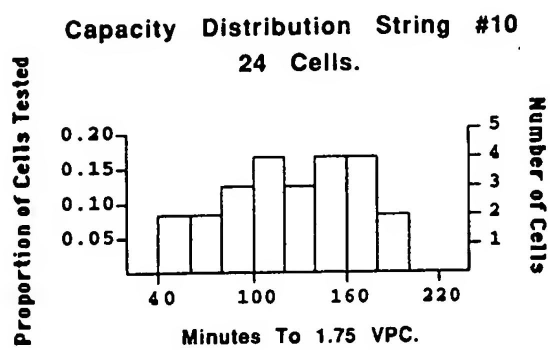


Figure 6

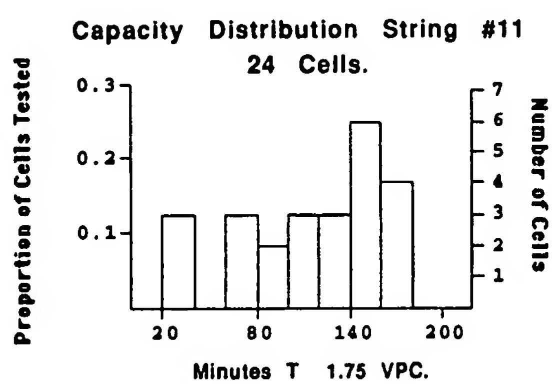


Figure 7

Figure 8 shows the capacity distribution of all 168 cells of strings 9 through 15, all to 1.75 volts per cell.

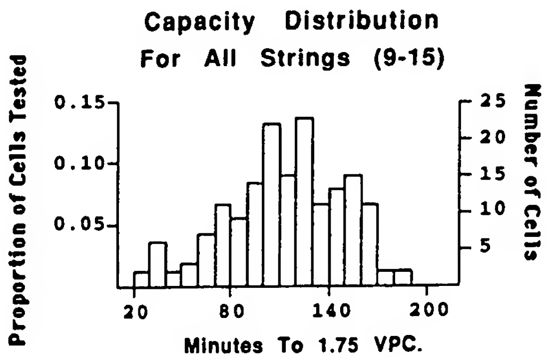


Figure 8

Figures 9, 10, 11 and 12 show similar capacity distributions, both for individual strings and for all 168 cells of strings 2 through 8 for capacity measured to 1.80 volts per cell.

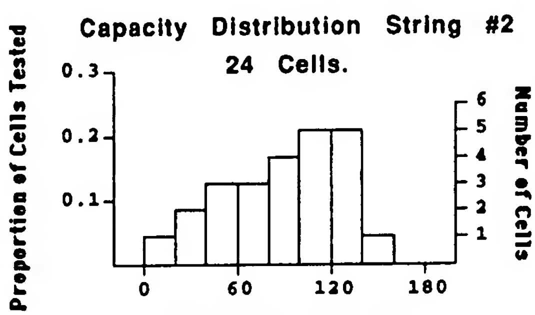


Figure 9

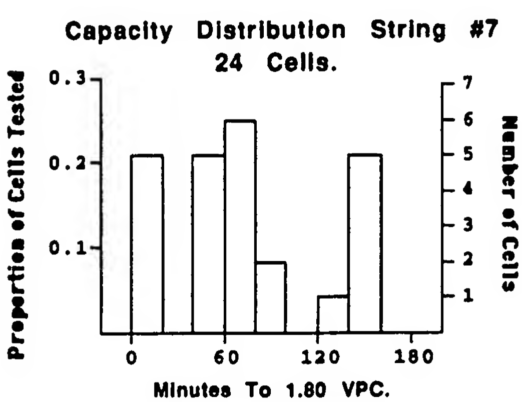


Figure 10

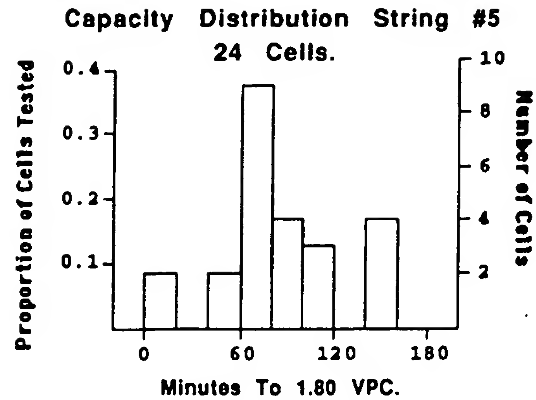


Figure 11

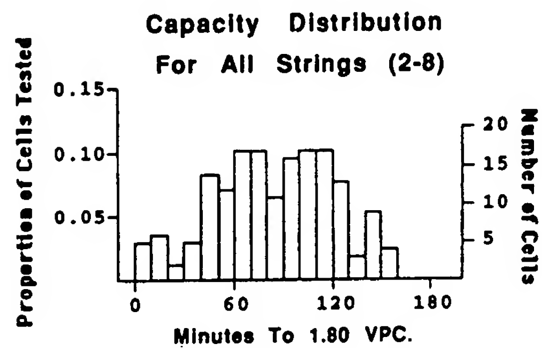


Figure 12

The contrast with the voltage distributions is astonishing. In every string and in the groups as a whole, capacities range from a few minutes to 180 minutes (approximately 100% capacity) despite the fact that individual cell float voltage values were completely within normal limits. Similar data for float voltage distribution and capacity distribution for 48 200 ampere-hour valve regulated lead-acid cells discharged at the two hour rate to 1.75 volts per cell are shown in Figures 13 and 14. Again, voltage distribution is within nominal, normal tolerances while capacities range from 80 to 115 minutes (66% to 96%).

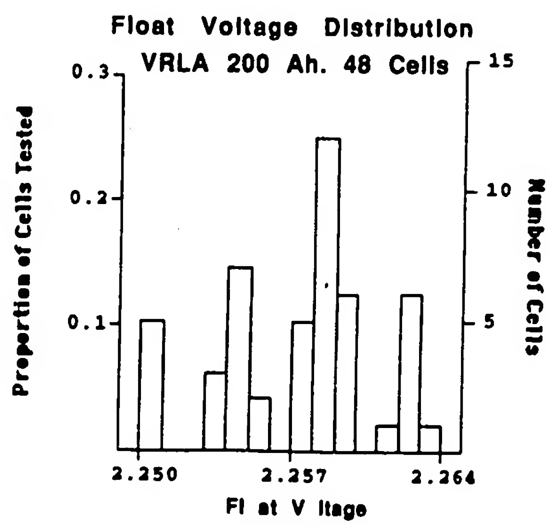


Figure 13

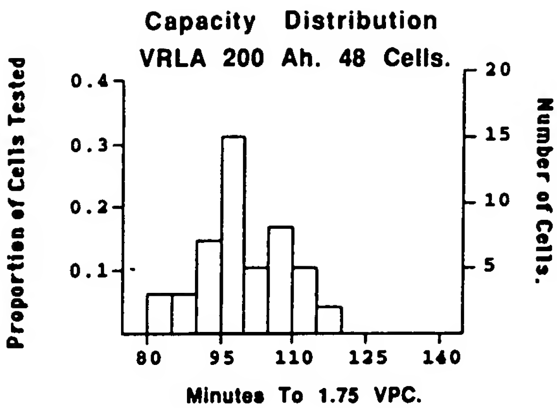


Figure 14

Even more significant is the attempt to correlate float voltage or specific gravity with cell capacity. While cell specific gravity is not directly measurable in a VRLA cell, it can be determined indirectly by measurement of cell open circuit voltage and calculated via the following formula:

•Specific gravity = Cell open circuit voltage - 0.85.

Figures 15, 16 and 17 show calculated specific gravity vs. capacity for strings 9, 10 and 11 while Figure 18 shows specific gravity vs. capacity for all 168 cells in strings 9 through 15. There is obviously no correlation. (Note that R is the linear correlation coefficient. In our data analysis, we have utilized R^2, the squared multiple correlation coefficient.)

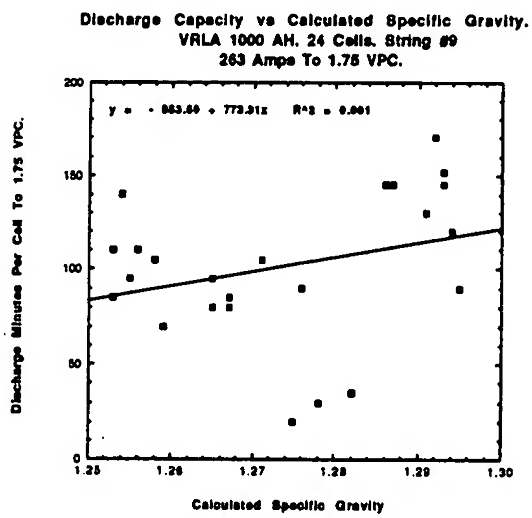


Figure 15

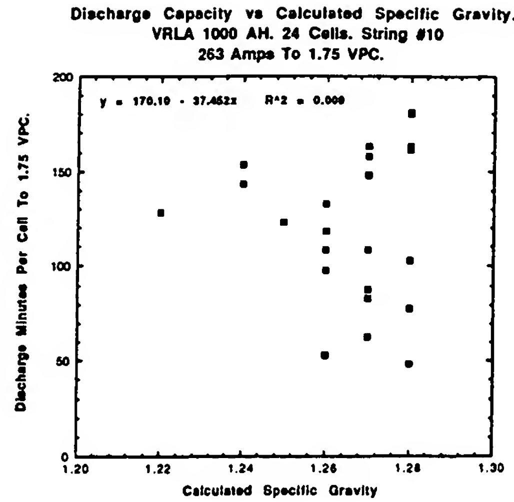


Figure 16

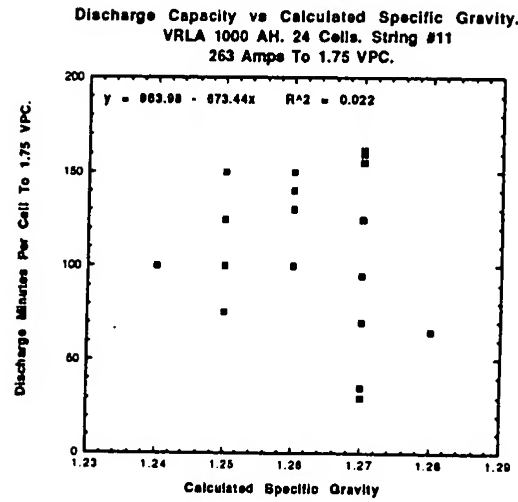
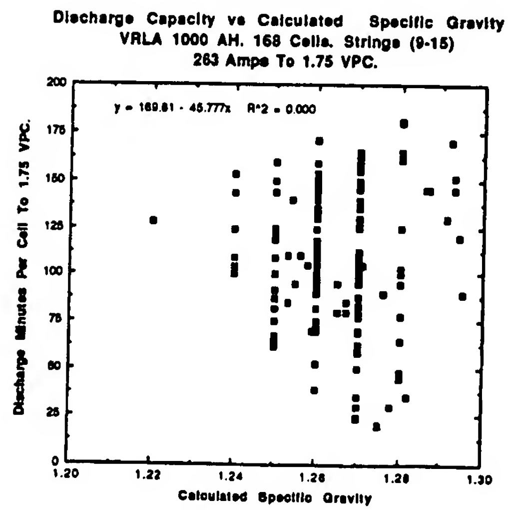


Figure 17



Figures 19, 20 and 21 show cell float voltage vs. capacity for the same three strings while Figure 22 shows float voltage vs. capacitv for all 168 cells of strings 9 through 15.

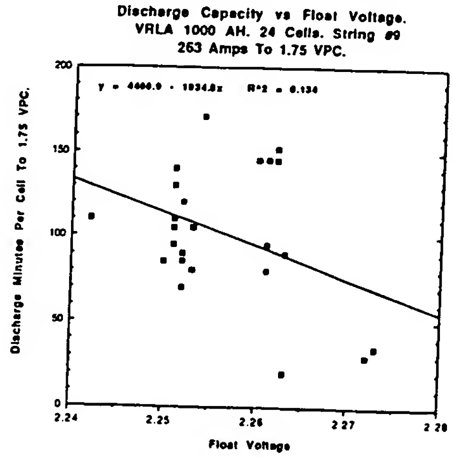


Figure 19

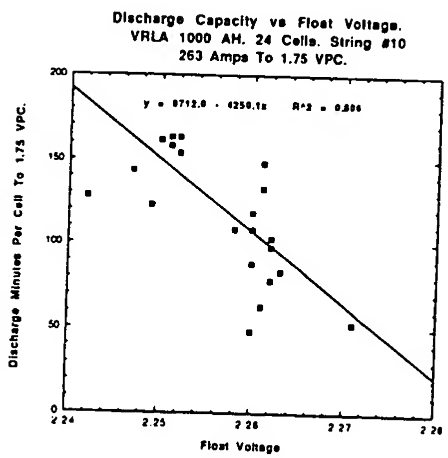


Figure 20

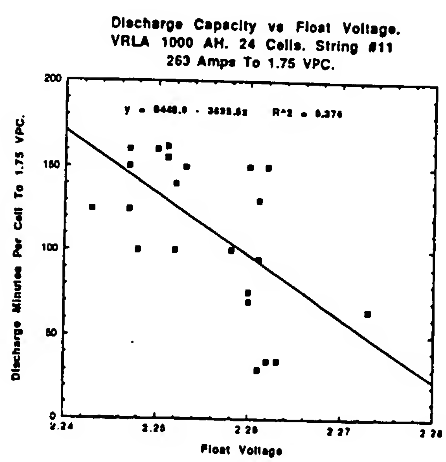


Figure 21

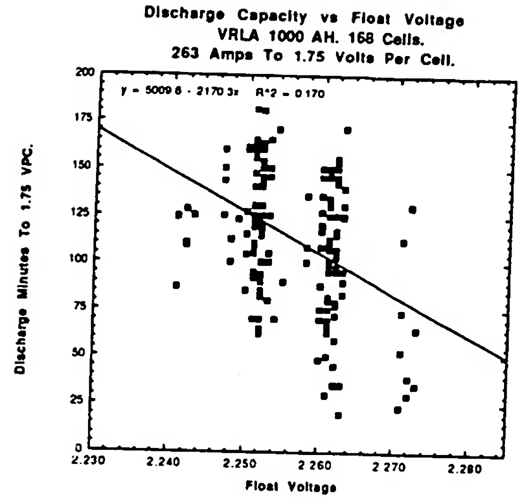


Figure 22

Figure 23 shows float voltage vs. capacity for the 48 200 ampere-hour cells. Although some of the correlation plots show a small but finite value of correlation, and the computer can draw a regression line, in no case would this "correlation" be statistically significant and be of practical use in predicting capacity behavior from float voltage.

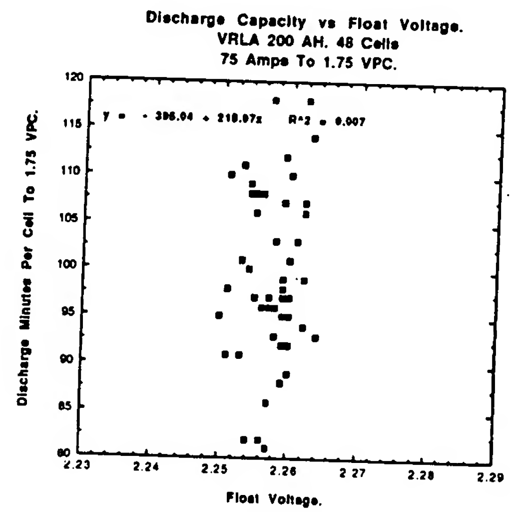


Figure 23

Charact ristics of Conductanc Measur ments:
Table 1 shows the results of conductance repeatability measurements on all 24 1000 ampere-hour cells of string 9 of the telephone transmission plant. In all but three cases, conductance values are repeatable to ± 0.01 Kilomhos (KiloSiemens) (± 0.5%). In the three cases, repeatability is within ± 0.02 Kilomhos (KiloSiemens).

Conductance Repeatability Test.

Conductance Measurements KMhos (KSiemens)

Cell#	G(1)	G(2)	G(3)
1	2.650	2.680	2.680
2	1.940	1.960	1.960
3	1.830	1.850	1.860
4	2.430	2.460	2.470
5	2.300	2.310	2.310
6	1.850	1.870	1.850
7	1.980	1.990	2.000
8	2.100	2.130	2.120
9	1.940	1.960	1.960
10	1.580	1.590	1.590
11	2.300	2.310	2.310
12	1.550	1.560	1.550
13	3.010	3.010	3.050
14	2.080	2.070	2.080
15	2.740	2.750	2.760
16	2.350	2.360	2.350
17	2.660	2.680	2.680
18	2.440	2.450	2.450
19	2.440	2.450	2.450
20	1.980	1.980	1.980
21	2.350	2.360	2.360
22	1.450	1.460	1.450
23	2.350	2.340	2.350
24	1.970	1.960	1.950

Table 1

Figures 24, 25 and 26 show results of conductance measurements taken on individual high, medium, and low conductance cells during the discharge of string 1 at the telephone transmission office. These data were obtained by momentarily interrupting the discharge, taking conductance readings, and then continuing the discharge. On initial examination, the data of Figure 24 and 25 do not appear to show the expected performance of conductance on discharge, i.e: conductance slowly decreasing during the initial phases of discharge and then decreasing more rapidly as the discharge continues to completion.

Conductance & Voltage Profile
During Interrupted Discharge Tests.
VRLA 1000 AH. String #1
263 Amps To 1.84 VPC.

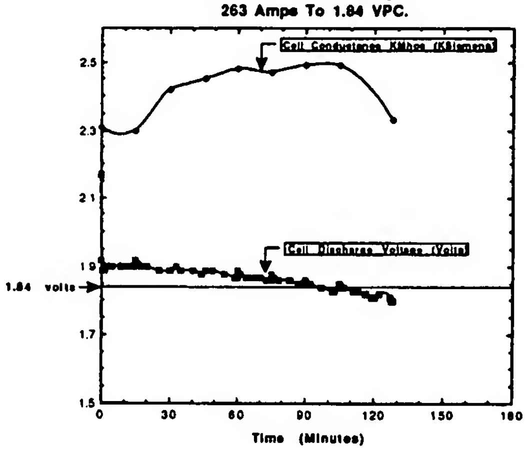


Figure 24

Conductance & Voltage Profile
During Interrupted Discharge Tests.
VRLA 1000 AH. String #1
263 Amps To 1.75 VPC

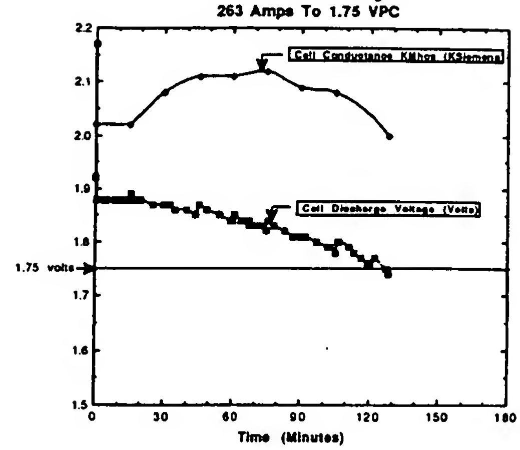


Figure 25

Instead, for Figures 24 & 25, conductance increases by 5 to10% for the first 30 to 40 minutes of discharge, then levels off, until cell voltage approaches 1.84, after which conductance drops rapidly. This appears understandable, if one considers the increasing electrolyte conductivity which occurs as the specific gravity decreases from 1.300 at full charge to approximately 1.260-1.270 after the first 30 to 40 minutes of discharge. Conductivity then becomes approximately constant until cell voltage drops below 1.84, and then conductivity decreases rapidly. Figure 26, which represents a low conductance and very low capacity cell, shows both voltage and conductance dropping steadily from th start of discharge.

Conductance & Voltage Profile.
During Interrupted Discharge Tests.
VRLA 1000 AH. String #1
263 Amps To 1.75 VPC.

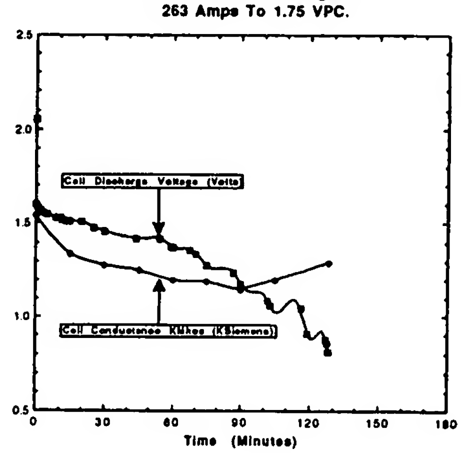


Figure 26

C nductance Measurements as Indicat rs f C ll Capacity: Single Cell Measurements

In marked contrast to the lack of correlation with capacity shown by float voltage or specific gravity (Figures 15 to 23), the correlation of capacity and conductance is extremely good. Figures 27, 28 and 29 show capacity vs. conductance for the same strings shown in Figures 1, 2 and 3 with correlation coefficients (R^2) in excess of 0.82.

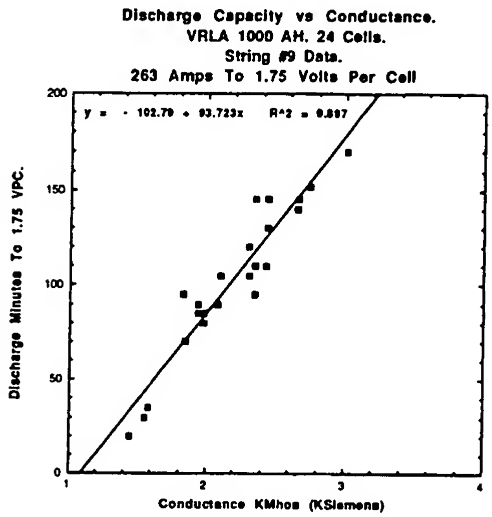


Figure 27

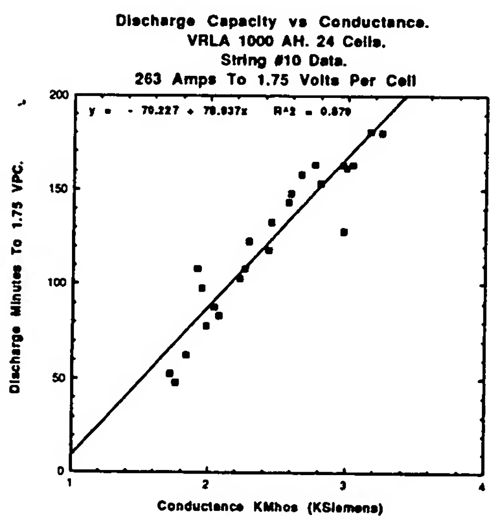


Figure 28

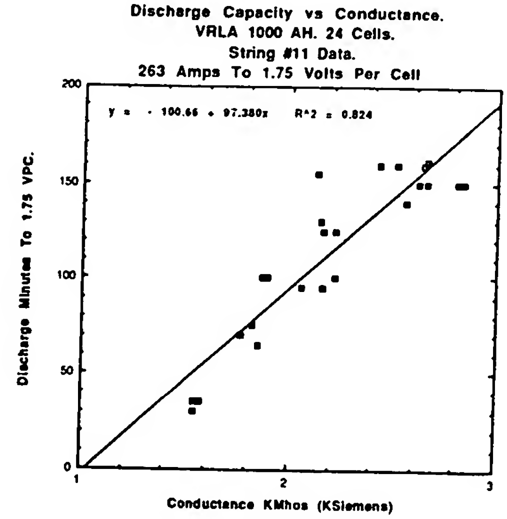


Figure 29

Figure 30 shows correlation of 0.78 between capacity to 1.75 volts per cell and conductance for all 168 cells in strings 9 through 15.

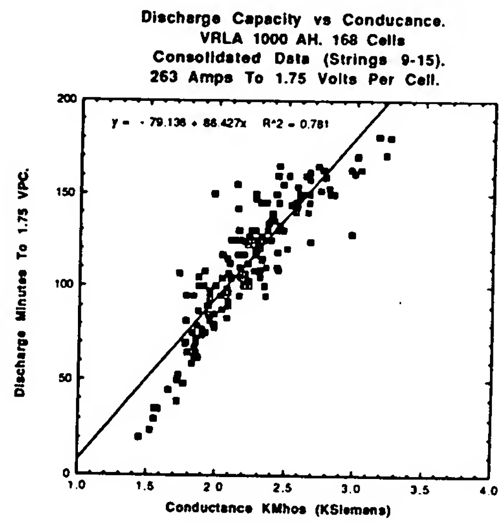


Figure 30

Figure 31 and 32 show correlation of conductance with capacity measured to 1.84 and to 1.80 volts per cell r spectively for the same group of 168 cells. Again, correlation co fficients range from 0.83 to 0.88 for the entire seven strings taken as a group. A similar group of 168 cells in strings 2 through 8 in the same t lephone transmission office were also tested at the same current (263 Amps) and capacities measured to 1.80 volts per cell.

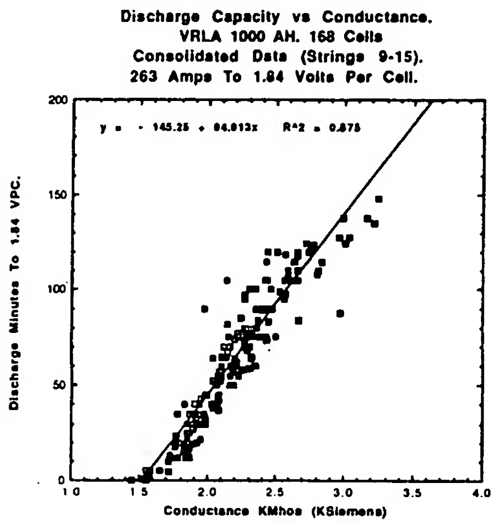


Figure 31

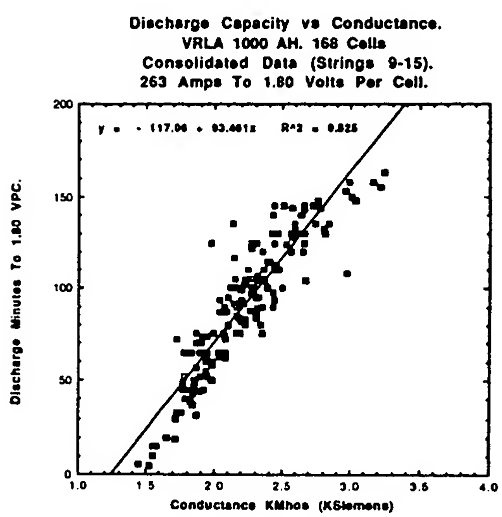


Figure 32

Figures 33, 34 and 35 show the correlation of capacity vs. conductance for strings 2, 7 and 5, representing the poorest (0.80), best (0.98), and "typical" (0.94) correlations respectively of the seven individual strings.

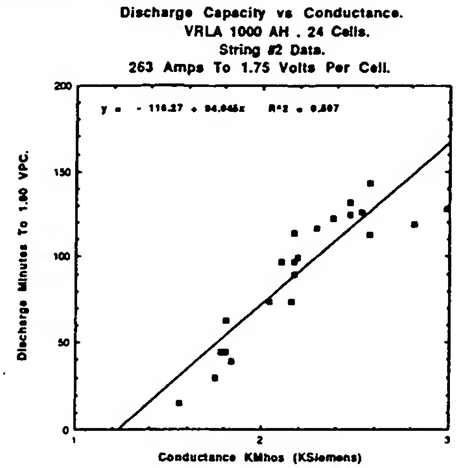


Figure 33

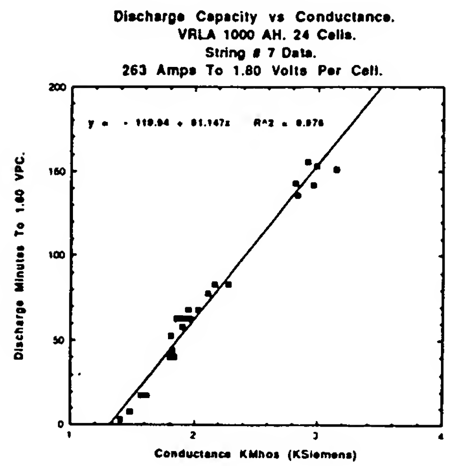


Figure 34

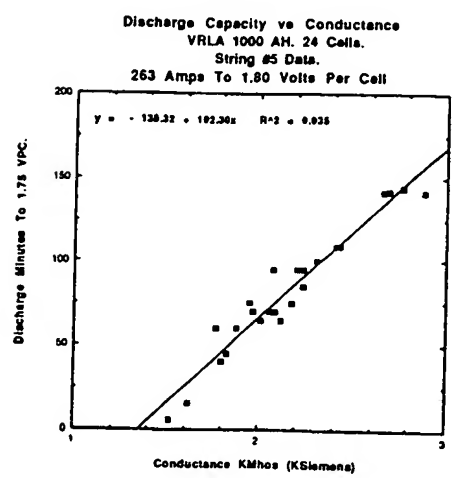


Figure 35

Figure 36 shows the combined correlation of strings 2 through 8 with a correlation coefficient of 0.88 for this entire 168 cell group.

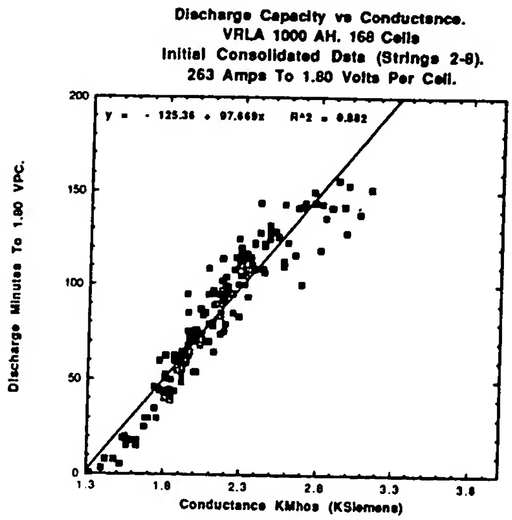


Figure 36

Data from strings 2 through 8 were used to calculate mean and standard deviation values of capacity for each 0.1 KMho (KSiemens) conductance interval with results calculated as regression lines for the mean and ± 2 standard deviation values. These statistical calculations were then overlaid (Figure 37) onto the data for strings 9 through15. This "exercise" provides an indication of the ability to predict the capacity of cells in strings 9 through 15 from their conductance based on the conductance/capacity values of strings 2 through 8. For strings 9 through 15, approximately 90% of the 168 cell population falls within the ±2 sigma prediction from strings 2 through 8.

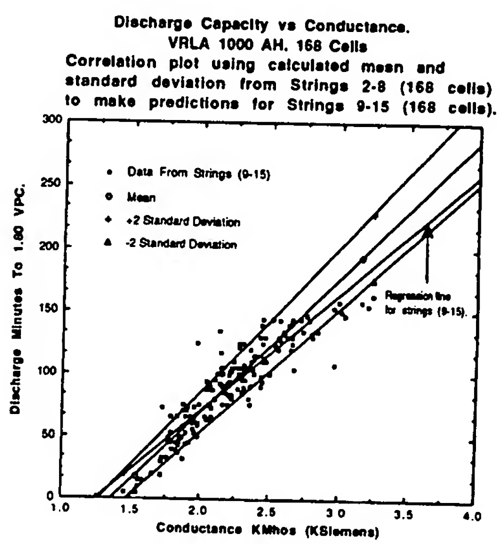


Figure 37

Figure 38 shows the capacity/conductance correlation of 0.75 obtained for the 48 200 ampere-hour cells for which Figure 23 had previously shown no correlation of float voltage vs. capacity.

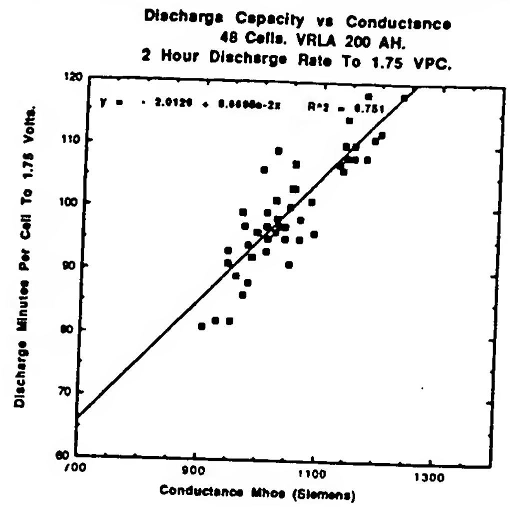


Figure 38

Measurements on Multicell Monoblocs

One of the benefits of valve regulated cells is their six or twelve volt monobloc combinations which minimize the number of individual units which must be interconnected. This is specially useful in high-voltage (120 to 380 Volt) UPS applications. The obvious drawback of such a monobloc is the inability to measure individual cell parameters, coupled with the probability that an individual cell failure will require replacement of th ntire monobloc, even though the other cells are still functioning properly. One such group of monoblocs was tested as part of this program. In a UPS system, twenty 6 volt 200 ampere-hour monoblocs were selected from the top tier of one string from a UPS plant containing three parallel strings of 60 monoblocs each (180 units in all: 60 x 6 = 360 volts per string). These were tested at the published one hour rate (100 amps) to 1.95 volts per cell (5.85 volts per monobloc). Correlation of discharge time to 5.95 volts per monobloc vs. conductance of the monobloc is shown in Figure 39.

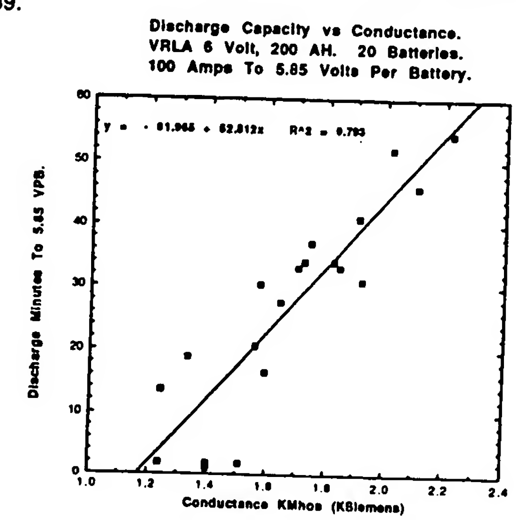


Figure 39

Again, we see a high degree of correlation of capacity with conductance over a wide range of capacities from three minutes to 55 minutes to the 5.85 volt per unit end of discharge voltage. Th 20 cells were discharged in a series connected string to an av rage of 117 volts (5.85 volts x 20) end of discharge voltage. Individual monobloc voltages at the string cutoff voltage of 117 volts are plotted vs. conductance in Figure 40. Again, a significant correlation is indicated.

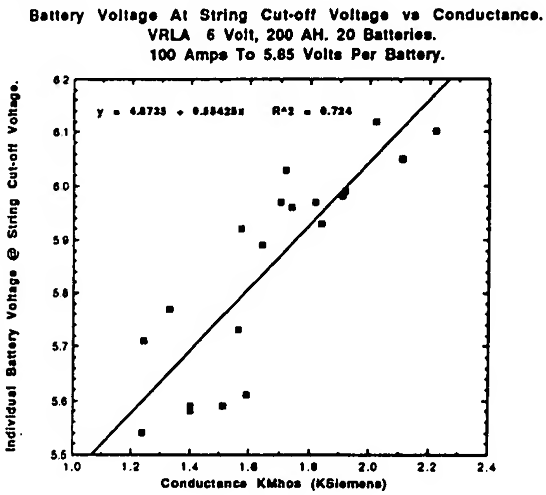


Figure 40

While the above tests represents the only group of monoblocs tested in this study for both capacity and conductance to date, the detailed data obtained at the telephone transmission site allows us to "synthesize" monobloc results as if eight 3-cell monoblocs per string were being tested rather than the 24 individual cells. By considering cells 1-2-3, 4-5-6, 7-8-9, etc. as "equivalent monoblocs", we can calculate an equivalent conductance and an average capacity for each "equivalent monobloc" and test both the correlation of conductance vs. capacity for individual monoblocs, as well as for the entire string of "equivalent monoblocs". Table 2 shows the results of such a calculation for string 13, compared with actual conductance measurements made with the Celltron tester across each three cell group, (as if they were monoblocs). The calculated and measured results are identical, within the precision of the technique.

Comparison Of Measured vs Calculated 3 Cell ("Equivalent Monobloc") Conductance. String#13.

Cell Numbers	Calculated Equivalent Monobloc Conductance KMhos (KSiemens)	Measured Monobloc Conductance KMhos (KSiemens)
1-3	2.210	2.190
4-6	2.600	2.590
7-9	1.970	1.950
10-12	1.770	1.770
13-15	2.080	2.080
16-18	2.230	2.230
19-21	2.170	2.180
22-24	2.210	2.220

Table 2

"Synthesized" equivalent monobloc calculations were then performed on strings 2 and 13. Results for strings 2 and 13 are shown in Tables 3 and 4.

"Synthesiz d" Equivalent M n bl c (6 volt) Capacity and C nductance. String #2.

Cell	Time to 1.80 vpc. Minutes	Average Time to 1.80 vpc Minutes	Measured Cell Conductance KMhos (KSiemens)	Calculated Equivalent 6 V Monobloc Conductance KMhos (KSiemens)
1	119		2.810	
2	117	112	2.290	2.400
3	100		2.190	
4	44		1.810	
5	128	67	2.980	2.060
6	30		1.750	
7	97		2.170	
8	63	97	1.810	2.120
9	132		2.470	
10	113		2.570	
11	123	126	2.380	2.500
12	143		2.570	
13	97		2.110	
14	126	116	2.530	2.360
15	125		2.470	
16	44		1.800	
17	114	67	2.170	1.900
18	44		1.780	
19	39		1.840	
20	117	57	2.290	1.850
21	15		1.560	
22	74		2.160	
23	74	79	2.040	2.120
24	90		2.170	

Table 3

"Synthesized" Equivalent Monobloc (6 volt) Capacity and Conductance. String #13.

Cell	Time to 1.80 vpc. Minutes	Average Time to 1.80 vpc Minutes	Measured Cell Conductance KMhos (KSiemens)	Calculated Equivalent 6 V Monobloc Conductance KMhos (KSiemens)
1	99		2.280	
2	94	99	2.040	2.210
3	104		2.310	
4	114		2.390	
5	104	121	2.670	2.600
6	144		2.780	
7	49		1.860	
8	99	64	2.200	1.970
9	44		1.890	
10	94		2.200	
11	19	39	1.710	1.770
12	5		1.530	
13	39		1.820	
14	89	71	2.310	2.080
15	84		2.180	
16	144		2.570	
17	74	99	2.070	2.230
18	79		2.100	
19	49		1.770	
20	124	92	2.530	2.170
21	104		2.370	
22	94		2.440	
23	84	81	2.300	2.210
24	64		1.960	

Table 4

String data (Figures 41 and 42) show a correlation coefficient of 0.91 to 0.95 for the calculated "equivalent monoblocs". Likewise, individual monoblocs with significantly weaker cells show good correlation between degraded average capacity for the specific monobloc and its equivalent conductance for that monobloc.

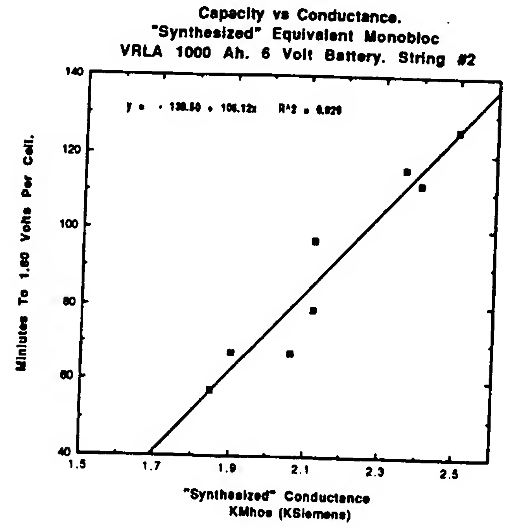


Figure 41

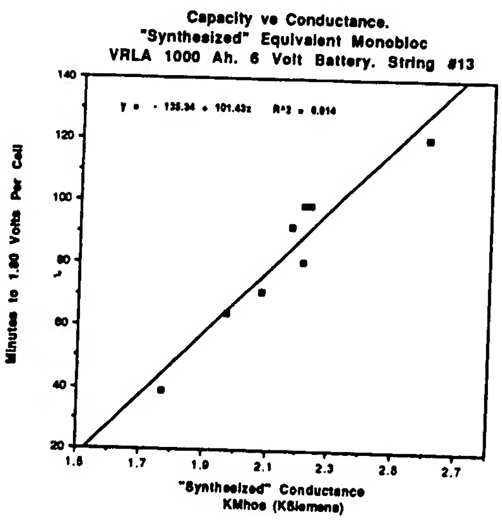


Figure 42

Relationship between Shape of Discharge Curves and Measured Conductance Values:

Since the conductance and discharge data taken at several sites include a significant number of good, mediocre, poor, and disastrously failing cells, analyses of the shapes of the discharge curves offers the possiblity to gain some insight into the failure modes at work. Figures 43 and 44 show two very different sets of discharge characteristics for poor and failing cells. Figure 43 shows discharge curves for three cells with differing conductance values. First, capacity and shape of discharge curve correlate directly with conductance values. However, note that while the two lower conductance cells both fail rapidly at 1.75 volts per cell, their capacity is not lost but is available almost completely at a 1.0 volt per cell cutoff. By contrast, the 5-cells shown in Figure 44 show no such characteristic. There is no indication that the weakest cell has retained its full capacity to a lower cutoff voltage (although 90 minutes to 1.5 volts is clearly superior to 0 minutes to 1.84 volts per cell). Likewise, the other cells do not appear to behave like the cells in Figure 43. Note, however that the performance to 1.84 volts per cell is directly in accord with the measured conductance values.

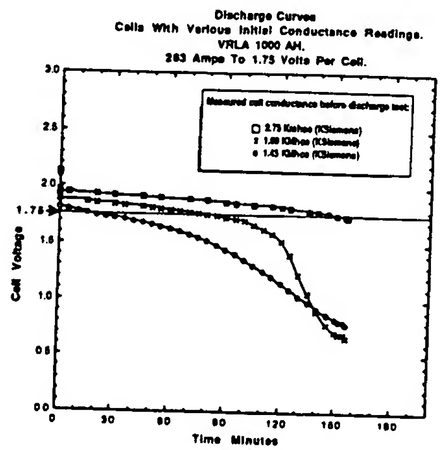


Figure 43

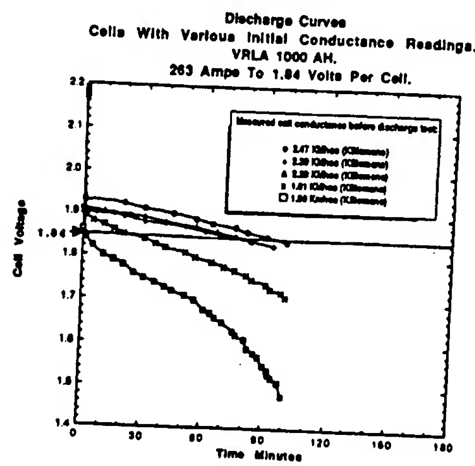


Figure 44

Finally, four discharge curves are shown in Figure 45 for 225 ampere-hour VRLA cells taken from a railroad signaling application. These show a classic pattern of discharge curves taken at increasing current densities. Professor Spinelli's paper[7] presented at the 1992 ILZRO conference uses computer modelling and documents the effects of 2 times, 4 times, and 20 times increase in discharge current density on the shape of the discharge curves. His calculated curves are shown in Figure 46. The similarity between the two figures (45 and 46) is striking. The obvious conclusion is that the four railroad signaling cells are behaving as though each was being discharged at successively higher loads. Since a constant discharge current was applied to all four cells, it would appear that the current density was increasing by multiple factors (similar to those of Prof. Spinelli's model) from the best to the worst, as a result of the loss of effective active material by any one of several possible mechanisms.

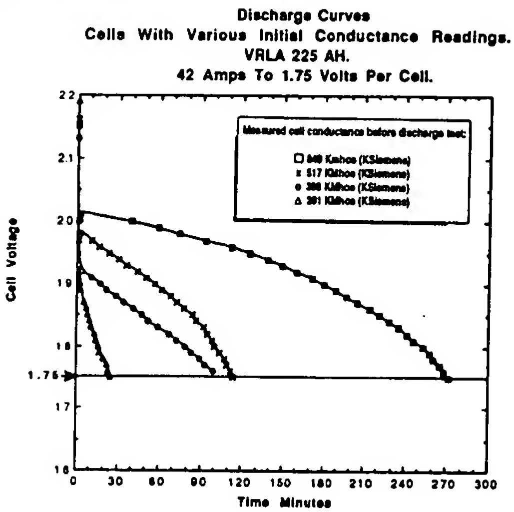


Figure 45

Discharge curves
at different rates
(Reprinted From Ref. 7)

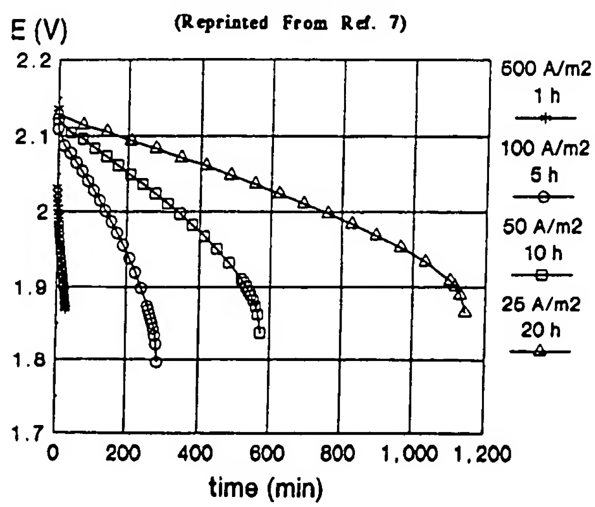


Figure 46

Post mortem teardown diagnostics are being scheduled for all of these cells and should be reported during the actual presentation of this paper in October. We are hopeful that these teardown diagnostics will shed light on the cause(s) of the good, mediocre, poor, and catastrophic performances observed among cells of identical vintage and within the same series string in these multi-parallel-string power plant designs, and for cell failures in some of the other applications for which test results have been presented.

Temperature Effects During Discharge:
While perhaps only indirectly related to conductance, thermal effects during discharge will be of interest to many readers. Figure 47 shows the results of temperature measurements made on the negative posts during discharge of three of the 336-1000 ampere-hour telephone cells tested. It seems surprising that temperature increases during discharge are of the order of 20° to 30° F (11° to 17° C), when the equivalent values for vented cells of similar size and at similar rates would be approximately 5° F (3° C). These temperature increases are, in general, but not in total agreement with the conductance values. Figure 48 shows temperature increase data during the same discharge on the same cells, except that the measurements were made on the jar wall between adjacent cells in the three cell battery assembly container. Again, temperature increases are of the order of 20° F (11° C), much greater than with their vented counterparts.

While many more measurements of this type remain to be made, it seems clear that temperature rise on discharge must be measured and be taken into account when calculating capacity for VRLA cells and that the values obtained will be a dir ct function of cell size, geometry of the cell installation, type of application and discharge rate. While the problems of VRLA cells due to temperature rise on charge have generally been appreciated, the above data indicates that temperature rise on discharge must be also carefully considered.

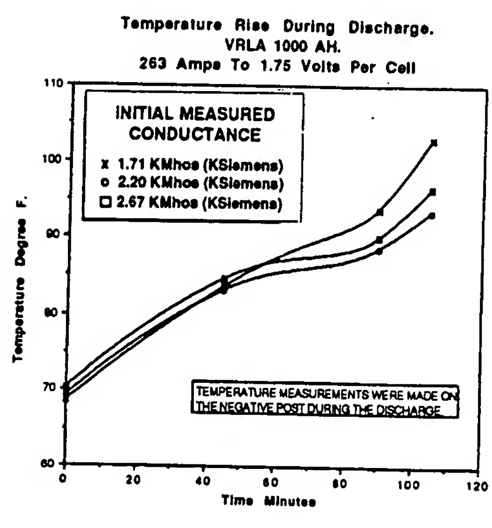


Figure 47

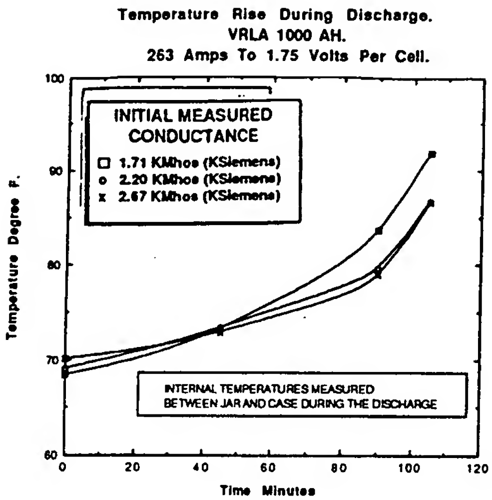


Figure 48

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

This study represents the initial phase of an ongoing program in which cell conductance, float voltage and specific gravity measurements have been made in conjunction with constant current discharge testing of approximately 500, four to six year old VRLA batteries. The batteries tested included a wide range of sizes, and were installed in a wide variety of telephone and UPS plant configurations. Capacities were found to range from over 5% to graeter than 100% of their rated values, with most strings tested containing this full spectrum of capacity values. From the results to date we can conclude:

1. No correlation exists between specific gravity (calculated from open circuit voltage) and measured ampere-hour capacity.
2. Very weak, statistically insignificant correlation exists between individual cell float voltage and measured ampere-hour capacity.
3. A high degree of correlation (R^2 of 0.80 to 0.98) exists between ampere-hour capacity and cell conductance, as measured with a Midtronics Celltron conductance tester, and monobloc battery conductance as measured with a Midtronics Midtron conductance tester.
4. This correlation is equally high for VRLA cells ranging from 200 to 1000 Ah in size, in series strings of 48 to 380 volts, and in plants containing as few as three to as many as 18 battery strings in parallel.
5. In telephone transmission usage, correlation between conductance and capacity is high, to end voltages of 1.84, 1.80 and 1.75 volts per cell.
6. Both individual cell and 6 volt monoblocs, show equally high correlation between conductance and measured ampere-hour capacity.
7. in the large 18 string telephone plant, conductanc /capacity correlation results on a group of 168 cells (seven-24 cell parallel strings) were successfuly utilized to statistically predict the capacity distribution of a second set of 168 similar cells in seven additional battery strings in the same telephone office, based on their measured conductance values.
8. Evaluation of a sample of the approximately 500 discharge curves available from this study indicates an unexpected (and in some cases, unique) variety of voltage-time characteristics for the various types of capacity failures observed. Further study of these curve shapes is required and will be accompanied by diagnostic, tear-down post mortem, in an attempt to understand the various types of failure modes which they represent.

Recommendations

Based on the high degree of correlation found in this initial study between cell conductance and available ampere-hour capacity, several recommendations seem appropriate:

1. Currently available conductance testers can be used effectively to derermine the state of health of Absorbed Glass Mat (AGM) VRLA cells and monobloc batteries in place of traditional methods which have proven to be ineffective.
2. Additional tests of other cell sizes, designs, types and applications are needed, with a major effort directed at VRLA gel designs. Flooded (vented) cell testing should also be included, in order to confirm the full range of capability of conductance to predict capacity.
3. Consideration should be given to the use of conductance measurement as an appropriate diagnostic for use in the remote battery monitoring systems currently being considered, actively being designed, or already in use. The data obtained in this study clearly indicate that conductance is a more useful diagnostic than cell voltages, which are currently being monitored in existing remote monitors.
4. Within most of the individual parallel strings in the same battery plant, a wide range of capacities has been ob served on identical cells This appears surprising, and needs more detailed diagnostic evaluation. The surprising shapes and variability of some of the discharge curves also need further evaluation. The effects of multi-string parallel operation of VRLA cells deserves further study.
5. Finally, the unusually high temperature rise during discharge requires further study.

These recommendations are expected to be included as part of this ongoing study.

Acknowlegement:
The authors would like to acknowledge the significant contribution of conductance and capacity test data provided by Mr. D. Ogden, Ogden Power, Inc.

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